Army Research Laboratory

Development of an Indium Gallium Arsenide (InGaAs) Short Wave Infrared (SWIR) Line Scan Imaging System

by David Y.T. Chiu and Troy Alexander

ARL-TR-5713 **September 2011**

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TR-5713 **September 2011**

Development of an Indium Gallium Arsenide (InGaAs) Short Wave Infrared (SWIR) Line Scan Imaging System

David Y.T. Chiu and Troy Alexander
Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
September 2011

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
November 2009 to July 2011

4. TITLE AND SUBTITLE
Development of an Indium Gallium Arsenide (InGaAs) Short Wave Infrared (SWIR) Line Scan Imaging System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
David Y.T. Chiu and Troy Alexander

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: RDRL-SEE-E
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-5713

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report describes the design, operation, and performance of a line scan imaging system using a one-dimensional (1-D) 256 indium gallium arsenide (InGaAs) photodiode linear array sensor that operates in the short wave infrared (SWIR) (0.8–1.7um) region. The system provides temporal profile images that show the outline, shape, size, height, and grey-shades of moving objects at a distance. These profile images allow low bandwidth and low power operation for detection and easy identification of human and nonhuman objects. The system is suitable for various covert Intelligence, Surveillance and Reconnaissance (ISR) operations in military or border security environments. It is inexpensive, estimated to be about 10–20% of what a regular two-dimensional (2-D) SWIR imaging system costs.

15. SUBJECT TERMS
SWIR, line scanner, profiling scanner, line scan imaging system, InGaAs, ISR, detection & identification

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			David Y. T. Chiu
Unclassified	Unclassified	Unclassified	UU	50	19b. TELEPHONE NUMBER (*Include area code*) (301) 394-0052

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

INTENTIONALLY LEFT BLANK.

1. Background and Introduction

Camera systems used in object detection and identification applications often require relatively high resolution in their output images to provide sufficient details needed to perform the required tasks. High resolution, however, is often accompanied with high bandwidth and high power consumption, which in turn leads to high operational cost. In operations where resources are limited and bandwidth becomes the primary constraint, resolution may need to be compromised if the operation is to be carried out. Currently, the Army's G2 (Intelligence) staff has an operational need for a low bandwidth system to detect and identify human and nonhuman objects. Images from regular cameras cannot meet the low bandwidth requirement. Profiling images provide information on the outline, shape, size, and height of an object at a much lower solution than regular images, but with enough detail to distinguish human and nonhuman objects, so such a system can meet the low bandwidth requirement.

The Radiometric Sensor Development and Applications Team of the Sensors and Electron Devices Directorate at U.S. Army Research Laboratory (ARL) has been involved in the study of two-dimensional (2-D) profiling scanner systems to investigate their operational characteristics, performance, and effectiveness in detecting and identifying targets in the battlefield and in homeland security environments. The first development efforts started about four years ago with a proof-of-principle ―doorframe" design that uses 16 light emitters and sensors and a tripwire detection method implementation that successfully demonstrated the feasibility of obtaining profiling images to detect and identify objects moving across a doorframe. A second system using a 320x240 infrared (IR) video camera was later developed that demonstrates a capability to detect and display profiling images of moving objects within the field of view (FOV) of the camera. The detailed design and performance of previous systems are documented in separate technical reports (*1*, *2*). This report describes a design using a one-dimensional (1-D) 256 indium gallium arsenide (InGaAs) photodiode linear array as the profiling sensor.

2. Scope

This report describes the design development, operation, and performance of a profiling scanner system using a 256 pixel InGaAs linear array sensor operating at the short wave IR (SWIR) (0.8–1.7 µm) range and a PC controller. Specifically, the following are discussed:

1. Key hardware components
2. Design
    - Overall design concept

- Design of control signals and timing with Waveform Editor
- Software design with LabVIEW

3. Output images
4. Summary

3. Key Hardware Components

The key hardware components used in this design consist of the following:

1. A 256 InGaAs linear array, as shown in figure 1.

Figure 1. Picture of the 256 InGaAs linear array sensor.

This is a sensor from Goodrich. Detailed specifications can be found at http://www.sensorsinc.com/arrays.html. Its dimensions are 2 in x 1 in x 0.5 in with an active area consisting of 256 pixels with a 50-micron pitch at 100% fill factor. The sensor operates at in the SWIR (0.8–1.7 µm) range.

2. A PC controller from National Instruments is shown in figure 2, consisting mainly of the PXIe-8106 embedded controller in a PXIe-1062Q chassis, along with the PXI-6255 data acquisition module (DAQ). Their specifications can be found at the respective Web site at the following links:

   - http://sine.ni.com/nips/cds/view/p/lang/en/nid/203441
   - http://sine.ni.com/nips/cds/view/p/lang/en/nid/202664
   - http://sine.ni.com/nips/cds/view/p/lang/en/nid/203008.

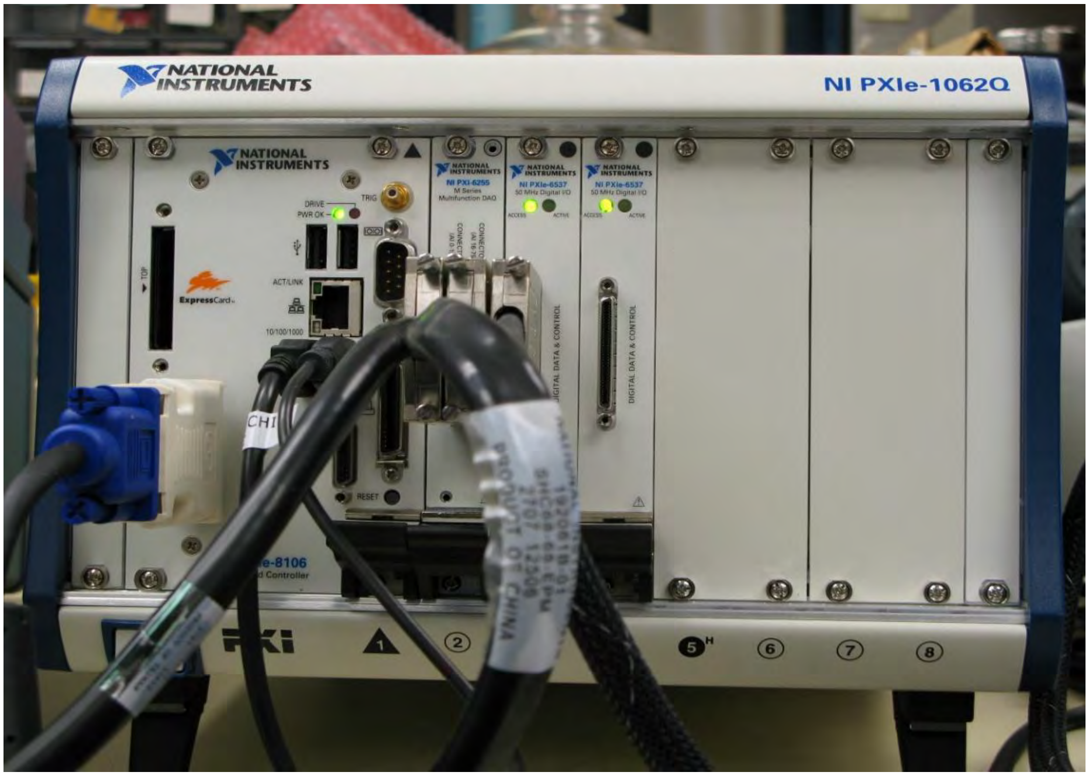


Figure 2. PC controller.

3. The sensor unit is shown in figures 3 and 4 (front and back views of the sensor head, respectively). It consists of a lens attached to a metal box, where the inside contains the InGaAs sensor array. The array is mounted on top of an *x*-*y* positioner that is attached to the back cover and positioned right behind the lens opening (black circular structure in center of the box). The circuit board in the left side of the box is the interface electronics. Descriptions of the lens and the interface electronics are as follows:

   - *Lens*: The glass of the lens is made out of uncoated BK7 material from ThorLabs that passes wavelength in the 350 nm–2.0 μm range.

   - *Interface electronics*: The interface electronics provide all the necessary interface signals and controls between the PC controller and the sensor array for proper operation of the system. These signals provide the monitoring and controls of various key operations in the sensor that affect the exposure time, operating temperature, readout of video data, etc. The schematic diagram of the interface circuitry is shown in figure 5. The key operations are described as follows:

     a. *Monitoring of operating temperature*: For safe and proper operation of the sensor array, the device has a built-in thermistor to allow monitoring of the device's operating temperature. To enable this feature, a circuit is included in the interface electronics to allow the PC controller's DAQ to continuously monitor the device's

operating temperature. The unity gain op-amp U2A (OP284EP) with its input pin3 (connecting to output pin7 of the array SU256LSB) and output pin1 going to the DAQ input is the portion of the interface that provides the temperature monitoring function. Complete analysis of the thermistor resistance as it relates to temperature reading is listed in appendix B. Interpreting the resistance values to temperature reading is performed in using the LabVIEW software. The LabVIEW front panel in appendix A shows the temperature reading in degrees Fahrenheit. The reading is updated at the sensor's operating refresh rate.

b. *Buffering and other funct*ions: The interface circuitry also provides functions for (1) providing a buffer for the control signals from the PC controller to the sensor to control its exposure time, video data readout, etc.; (2) selecting the sensor's operating mode, i.e., high dynamic range and high sensitivity modes, which allow operation of the device in high (outdoor) or low (indoor) ambient brightness, respectively; and (3) providing a unity gain buffer to connect the reference voltage to the photodiode substrate inside the senor chip to maintain proper operating voltage.

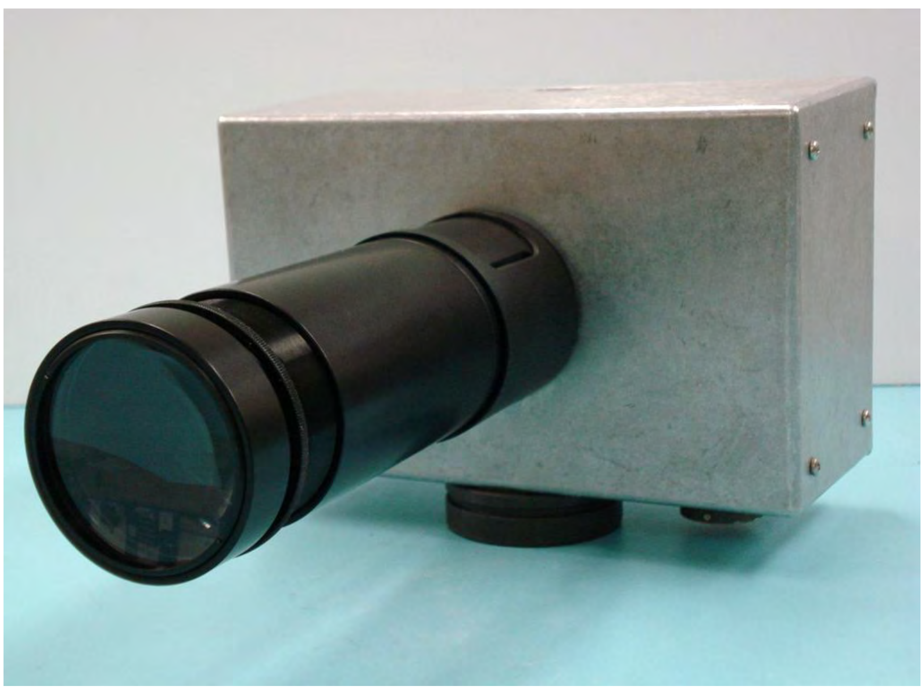


Figure 3. Picture of the sensor unit.

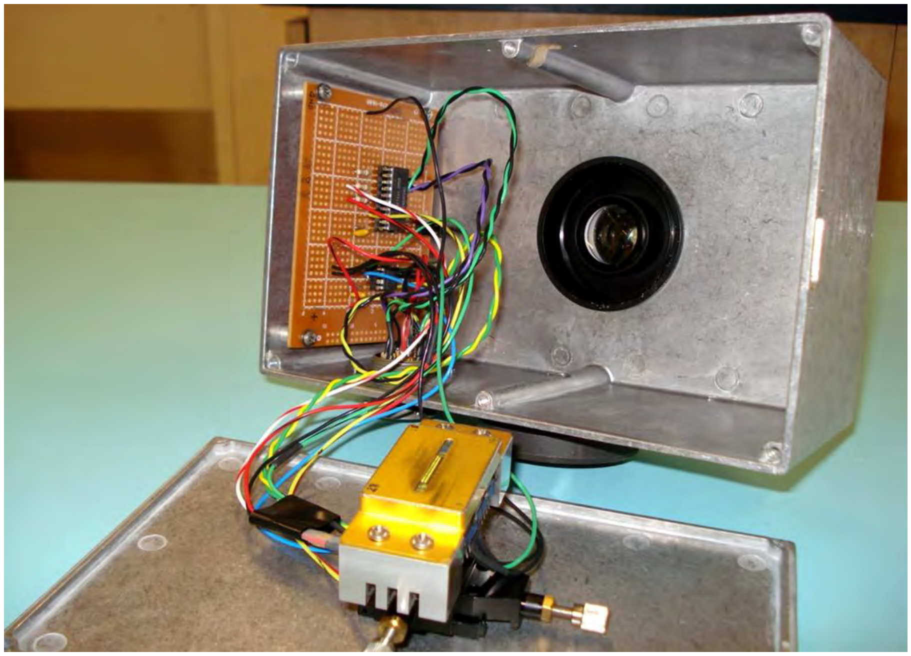


Figure 4. Picture of the InGaAs sensor and interface electronics behind the lens inside the sensor box.

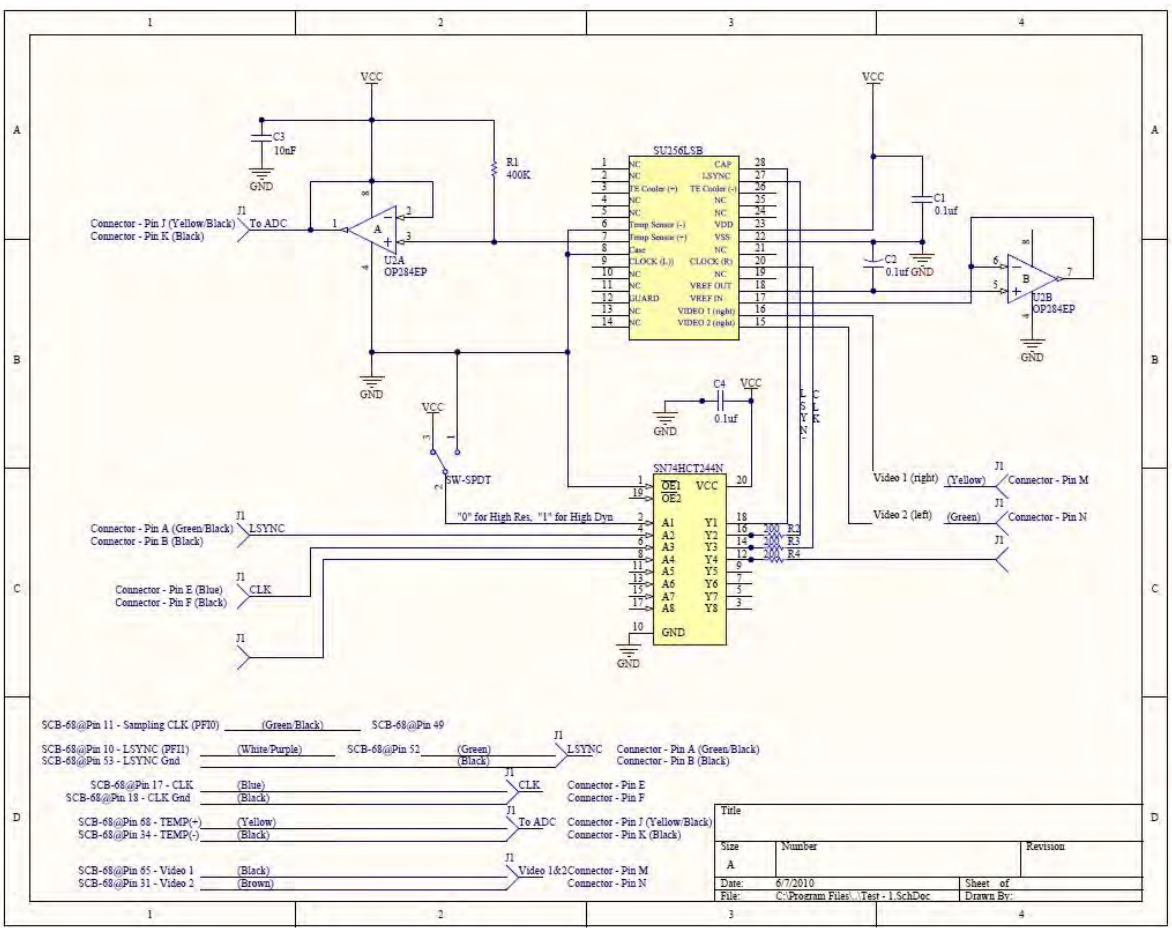


Figure 5. Interface circuitry schematic diagram.

Figure 6 shows a picture of the complete linear array profiling scanner hardware with the sensor unit on a tripod to the right and the PC controller to the left.

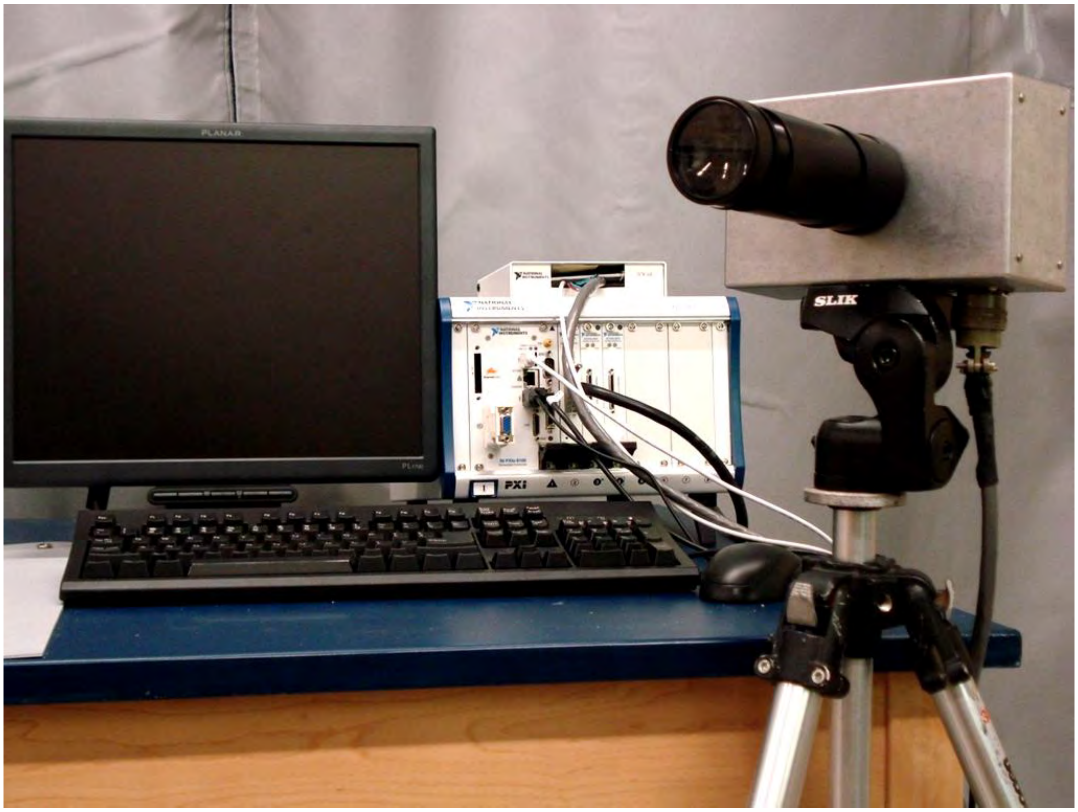


Figure 6. Picture of the linear array profiling scanner hardware.

4. Design

4.1 Overall Design Concept

The design concept behind the linear array SWIR profiling scanner is based on the ―tripwire” detection method that was used in previous designs for sensing of moving objects. Each of the 256 sensors in the array is used as a tripwire that starts from the front window of the sensor chip and extends outward to the outer limit of the imaging area covered by the lens. Objects moving across any portion of the tripwire can be detected if their surface temperatures exceed a pre-determined level, specifically, if they exceed the background temperature plus a pre-selected threshold value.

The following sections describe what is needed to control and operate the sensor array, and how the tripwire detection method is implemented in LabVIEW using the captured video data from the sensor.

4.2 Design of Control Signals and Timing with Waveform Editor

Operation of the sensor array is controlled by signals generated from the PC controller. These signals control the exposure time of the sensor and readout of its video data. Figure 7 shows the specific signals and timing diagram required by the sensor chip.

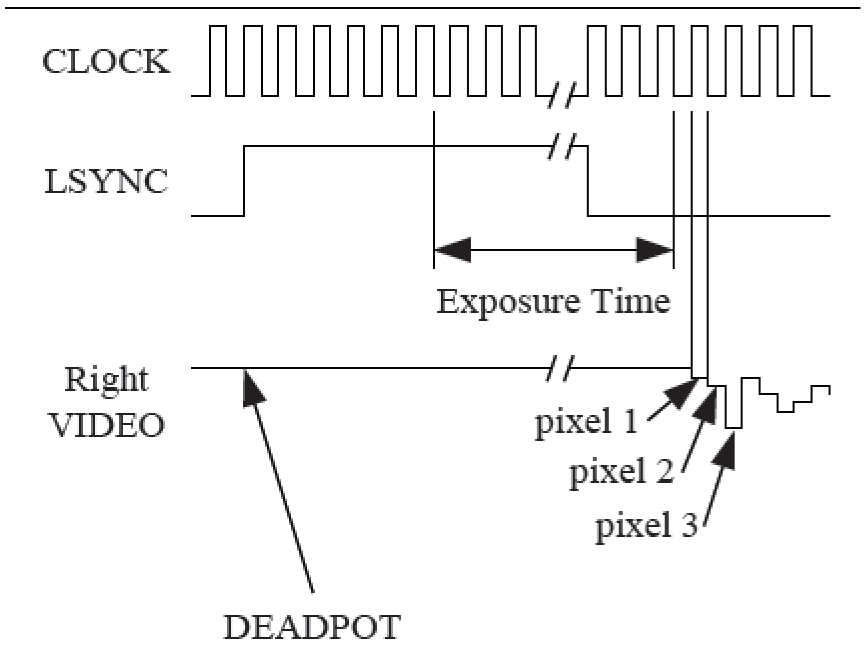


Figure 7. Signal and timing diagram required by the sensor array.

The CLOCK is a typical clock signal used in any digital system; it sets up the speed at which all other signals run. LSYNC controls the refresh rate for the sensor array. Depending on where the falling edge is set, it also controls the exposure time for each frame of data. As can be seen in the diagram, the exposure time is the time between the falling edge of the 6th CLOCK after the rising edge of the LSYNC and the falling edge of the 3rd CLOCK after the falling edge of LSYNC. The NI Waveform Editor is used in the PC to generate these timing control signals.

Figure 8 shows example of waveforms diagram for one frame of video operation. It consists of signals, 2X Clock, CLOCK, LSYNC, and Sample CLOCK. The timing of these signals controls the exposure time setting and video readout functions of the sensor array chip. Figure 9 shows what the waveform timing looks like in the start of a frame when the sensor is set to expose to light coming from the image. Video data readout occurs afterward when LSYNC goes ―low‖ The Sampling CLOCK is used to read out each pixel of video data. It is running at 2X Clock because the video is clocked out during both the falling and rising edges of the CLOCK (as shown in figure 7), effectively doubling the CLOCK rate. The same waveforms and operations repeat continuously for every frame.

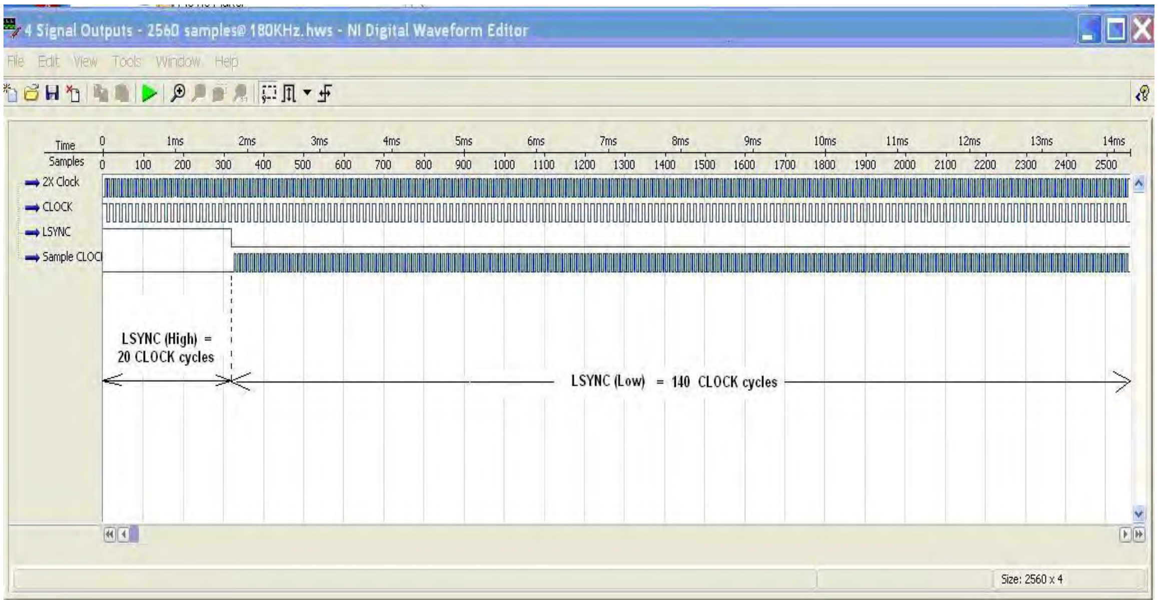


Figure 8. Control signal waveforms for one frame of video.

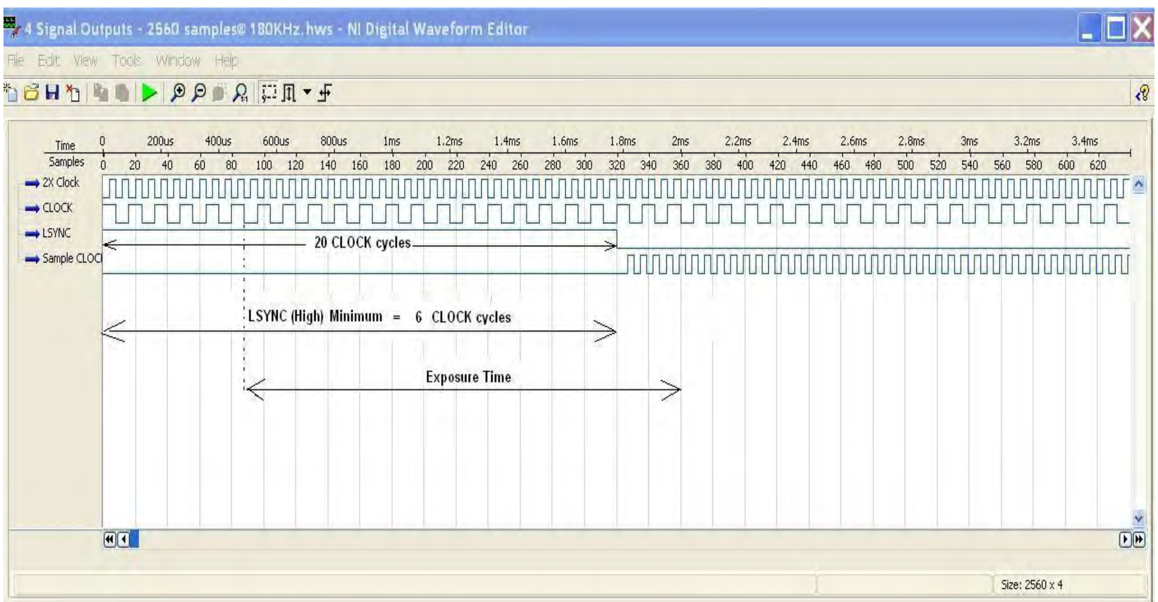


Figure 9. Close-up view of signal waveforms timing at the start of a frame.

Typical calculations for refresh rate, exposure time are shown as follows:

- *Refresh Rate*:

  The sampling rate used to generate the waveform is set at 180 KHz. This corresponds to 5.55 µs per sample. From figures 8 or 9 (figure at lower right), the total number of samples in one frame is set at 2560 for one frame. The refresh rate is therefore equal to 5.55 µs ×

2560 = 0.0142 s, or 1/0.0142 = 70 Hz. Because of the processing time and other overheads in the PC, the actual system operating rate is a little lower at about 53 Hz.

- *Exposure Time*:

  From figure 9, exposure time = 17 CLOCK cycles. Since each frame contains 160 CLOCK cycle (as shown in figure 8), each CLOCK is equal to (frame duration)/(number of CLOCK cycles), or 0.0142 s/160, which equals 88.8 μs. Thus, exposure time = 17 x 88.89 μs, or 1.51 ms.

4.3 Software Design with LabVIEW

A major part of the design is implemented in software using LabVIEW, which implements the tripwire detection method to establish a baseline, sets threshold values for the detection, monitors changes caused by presence of moving objects, processes the data collected, and displays the resultant profiling images. The program runs in a continuous mode. Appendix A shows the front panel and block diagram of the LabVIEW program in details. The plot on the upper left shows one frame of video data; it is continuously being updated at the refresh rate set by the LSYNC signal. The *x*-axis is the pixel acquisition time, showing when video data from each of the 256 sensor pixels are being acquired by the DAQ into memory. Video data are being acquired sequentially in time starting from the first pixel, thus, the left side of the *x*-axis represents the beginning of the acquisition (i.e., pixel 1) and the right side the end of acquisition, or pixel 256, for one frame of data. The *y*-axis represents the magnitude or value of each of the acquired video data. The profiling images are shown in three plots, the lower left plot and the two plots to the right. The lower left represents a plot of the profiling image using 16 of the 256 sensors, specifically, sensor pixels 9, 25, 41… to 249, each at 16 pixels apart. It has 16 individual *x*-axis points, corresponding to each of the 16 sensor pixels. The *x*-axis is the frame update time, and therefore, shows a real-time running chart of the 16 sensors. The *y*-axis shows the logical values (i.e., "1" or "0") of the corresponding video data from the 16 sensor outputs. The two smaller plots to the right are plots of profiling image using all 256 pixels. The two plots basically show the same information using different colors, serving the same purpose of displaying the output profiling image, but are used differently for software debugging purposes. These plots can be considered as three-dimensional (3-D) plots with *x*-axis being the time, specifically, the frame refresh or update time, and *y*-axis representing each of the 256 sensor outputs. The 3-D portion or the *z*-axis of the plots is represented by the intensity, or grey-shade, of the video data. The video data are normalized to 256 grey-shades and their values are plotted accordingly, with 0 at the lowest to 256 at the highest brightness/intensity. In comparison to the 16-pixel logical plot that runs in real time at the sensor refresh rate, the 3-D plots update every 400 frames. The 3-D plots, therefore, show what the last 400 frames of video data look like at 256 grey-shades. As such, the resultant image is a temporal profile of the moving object.

Following is a description of the sequence of functions that are performed in the software when system is operating:

1. *Selection of exposure time*: The exposure time of the sensor must be set at a level that is within the operating range of the sensor array so that imaging data can be captured at the proper level. The “Exposure Time” control button in the front panel allows for selections of various exposure settings.

2. *Collection of background temperature and selection of threshold value*: Once the exposure time has been selected, imaging data are captured as the temperature readings at each of the sensor pixels. They are stored in memory as each frame of data is updated. When the “Calibrate” button on the LabVIEW front panel is pressed, they are set as background temperature. Once the baseline is established, a threshold value can then be added to each of the stored values. Collection or capture of image data occurs every frame, but the calibration process occurs only when the button is pressed.

3. *Comparison to subsequent frames*: These threshold adjusted (TA) values are then used to compare to new data obtained from the subsequent frames as each frame is updated, any changes exceeding the TA values indicate the presence of an object—logic “1” is assigned to a variable (in memory) and values below are assigned as login “0” or no detection. This comparison operation occurs in every frame.

4. *Process and display of profiling image*: In the case of the 16-bit profiling plot, these individual logic variables are then stacked together to form the *y*-axis on an output display plot, with *x*-axis being the refresh update time of the sensor, which is set by the LSYNC signal. The output plot shows a real-time moving profile image of objects as they move across the image area. The area under each of the 16-channel *y* plots is filled with solid color so that a solid profile image of the object is shown. Each color bar represents the logic 1 value (detection) of each sensor, and the black or no color bar represents logic “0” (no detection). This operation repeats every frame.

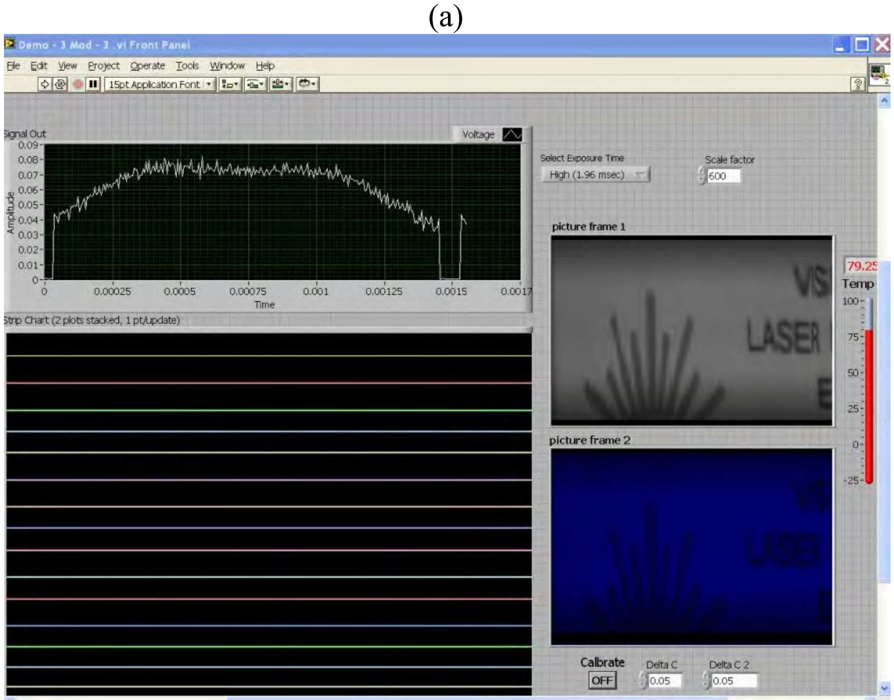
   In the case of the 256-bit or full resolution profiling plots, the actual magnitude or value of the video data is used for the plot instead of their “0” and “1” logical values. The actual values are normalized to 256 levels of intensity or grey-shades and the normalized values are plotted out as intensity. This plot is not running in real time, but updated every 400 frames. It effectively shows a picture of what the video data look like for the last 400 frames, with each frame consisting of a 256-pixel vertical line. As stated earlier, the resultant image is a depiction of the temporal profile of the moving object.

5. Output Images

5.1 Bench-top Test Images

To determine if all the hardware and software are functioning properly, a test scan was performed on a laser eye safety sign shown in figure 10a.

(a)



(b)

Figure 10. (a) Picture of a laser eye safety sign used for test scan image and (b) test scan image as shown on LabVIEW front panel.

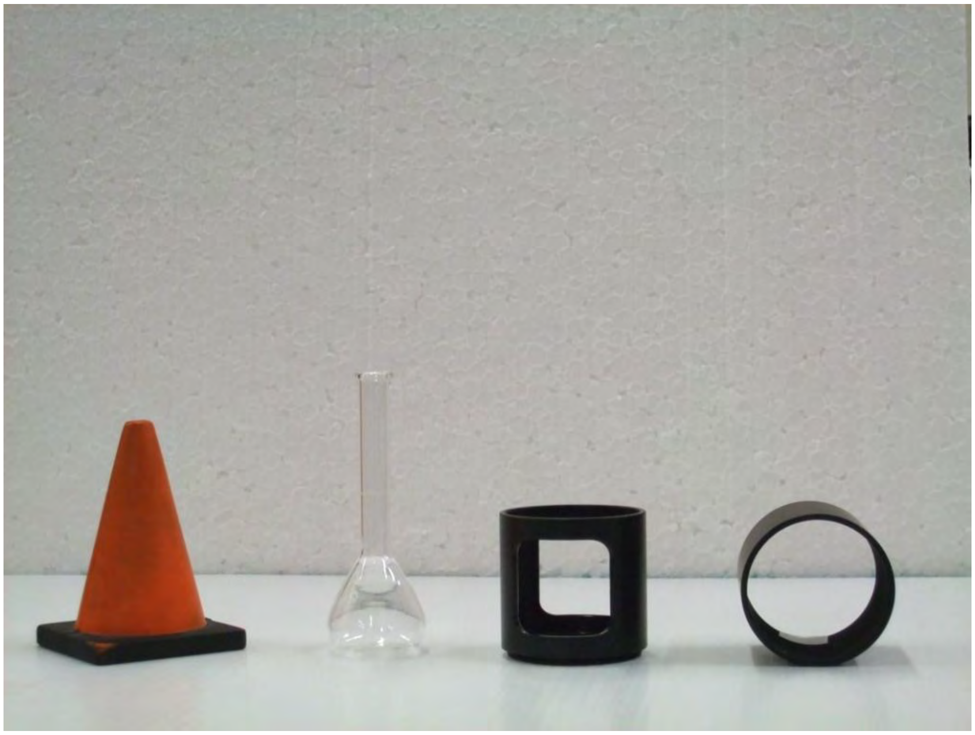
The scan was performed by first locating and positioning the sensor at a focus distance, and then moving it horizontally from left to right (i.e., scanning) across the target at a constant rate. Image data are collected continuously from frame to frame, as the sensor unit moves across. When 400 frames of data have been collected, they are displayed as scan images shown on the two right plots of figure 10b on the LabVIEW front panel. The lens used in the system for the test scan has a FOV that covers only a small portion of the sign, at the focus distance. The resultant scan images therefore show only the portion covered by the FOV during the scan (approximately a small portion near center right of figure 10). Different lens with larger FOV can be used to cover the whole sign. Nevertheless, the scan images in figure 10 verify proper functioning of the following operations:

1. Exposure time setting to the sensor array
2. Read out of video data from the sensor
3. Acquisition of video data by the DAQ to PC memory
4. Storage of data into memory
5. Recall and display of video data from memory

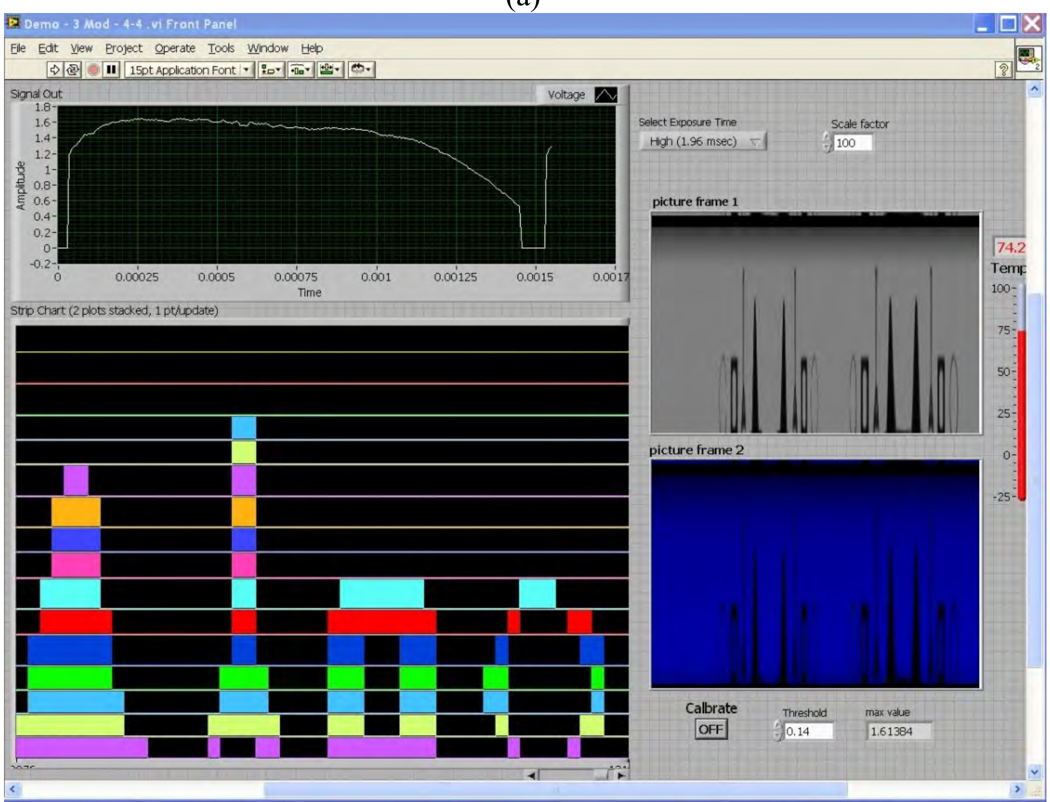
As such, the system's hardware and software are performing as intended.

The following show results of other bench-top tests.

The images in figure 11 are taken at focus distance ranging from approximately 5 to 10 ft inside the lab, with the sensor fixed at a focus distance. The scanning process was performed by moving the objects across the sensor at a relatively constant rate, with the camera/sensor at stationary position. Figure 11a shows picture of objects of different shapes and sizes, and figure 11b shows their scanned profiling image. Result shows the capability of the system in detecting, capturing, and displaying profiling images of objects of different shapes and sizes.



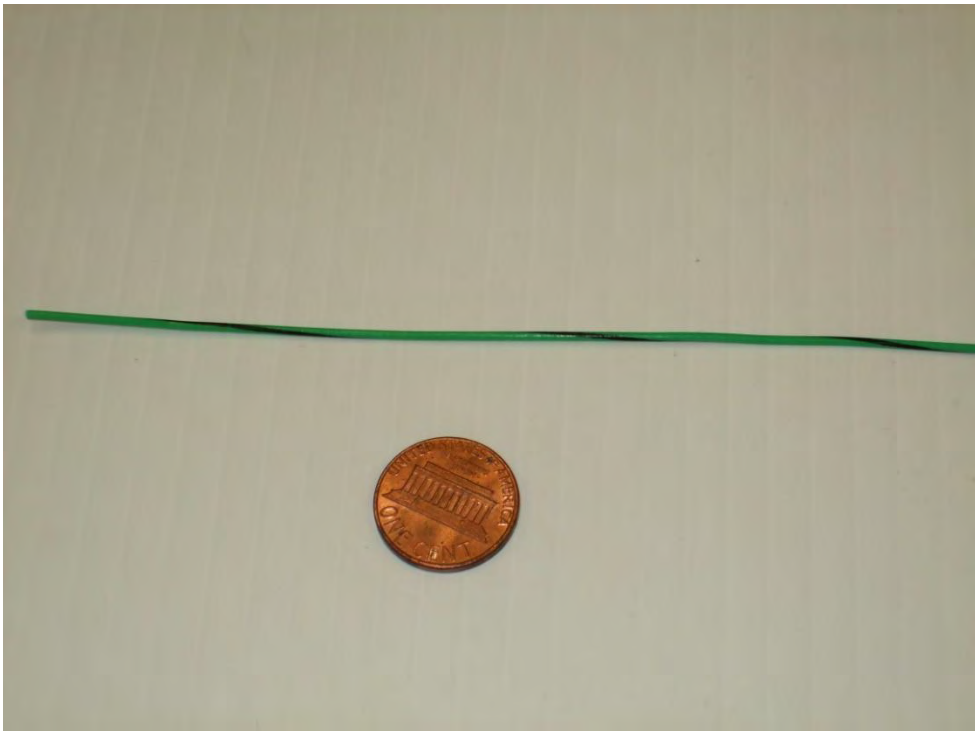
(a)



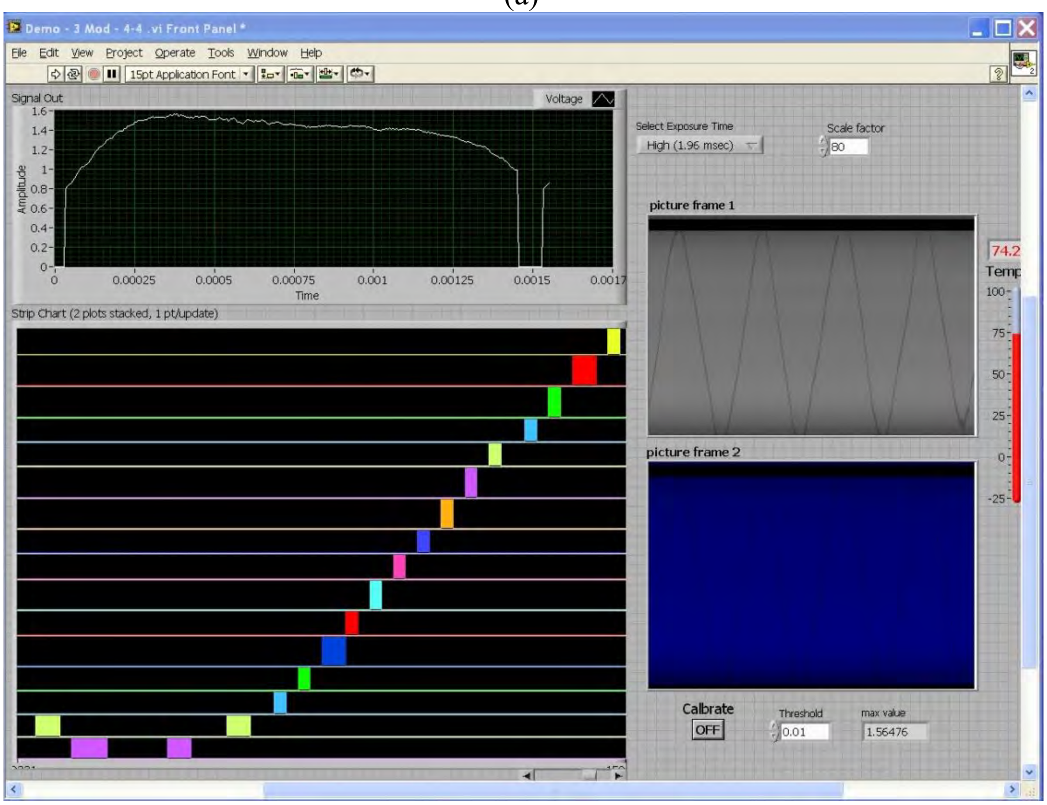
(b)

Figure 11. (a) Picture of four different shape objects and (b) profiling images of objects.

Figures 12a and 12b show the level of detail or resolution that the system is capable of detecting and capturing. A piece of wire with a diameter of about 1 mm as shown in figure 12a is moved up and down across the sensor at a focus distance of about 5 ft, the profiling images in right side of figure 12b (the sine wave lookalike curves) clearly show that each of the 256 sensors is detecting the wire as it moves across the array, and the image data are properly captured and displayed. A key objective of this test is to show what the hardware electronics and software are capable of performing at such resolution, as long as the optics can deliver the image with the sufficient details to the sensor.



(a)

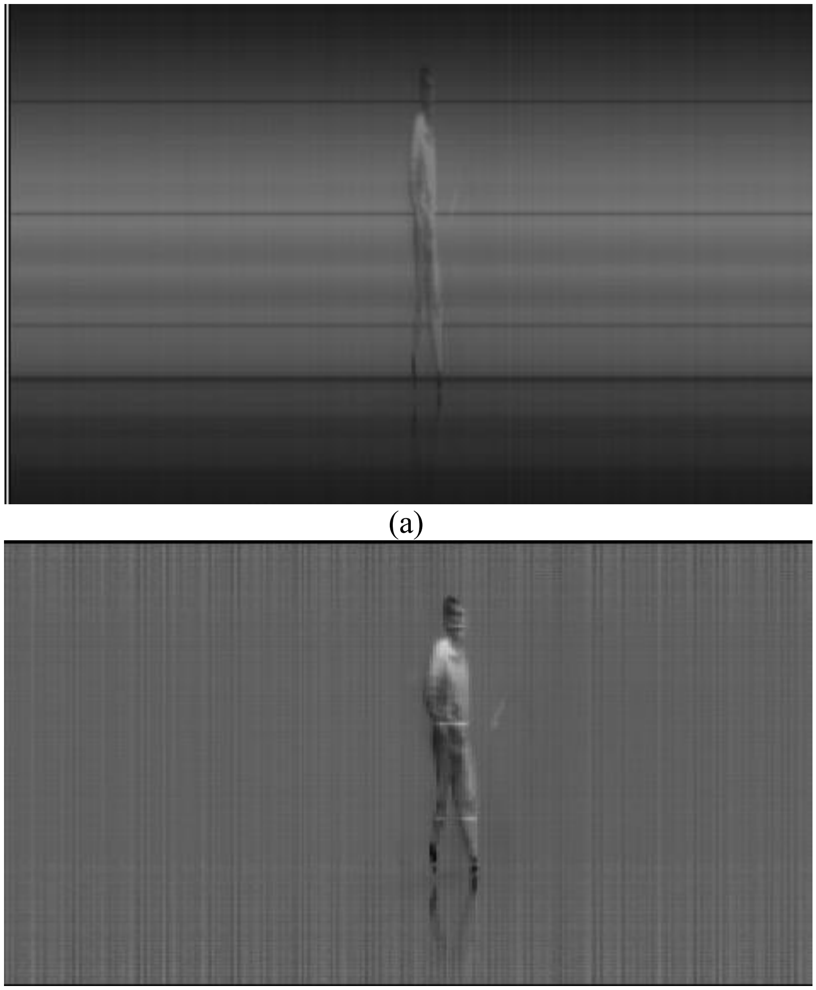


(b)

Figure 12. (a) Picture of a piece of wire (a penny is there for size comparison) and (b) profiling image of a piece of wire shown in figure 12a as it moves up and down across the sensor.

5.2 Test Images with Live Moving Objects

Figures 13 through 27 show how the system performs with live moving objects at longer distances.



(a)

(b)

Figure 13. (a) Image of a person walking scanned at distance of about 18–20 ft and (b) processed image of figure 13a.

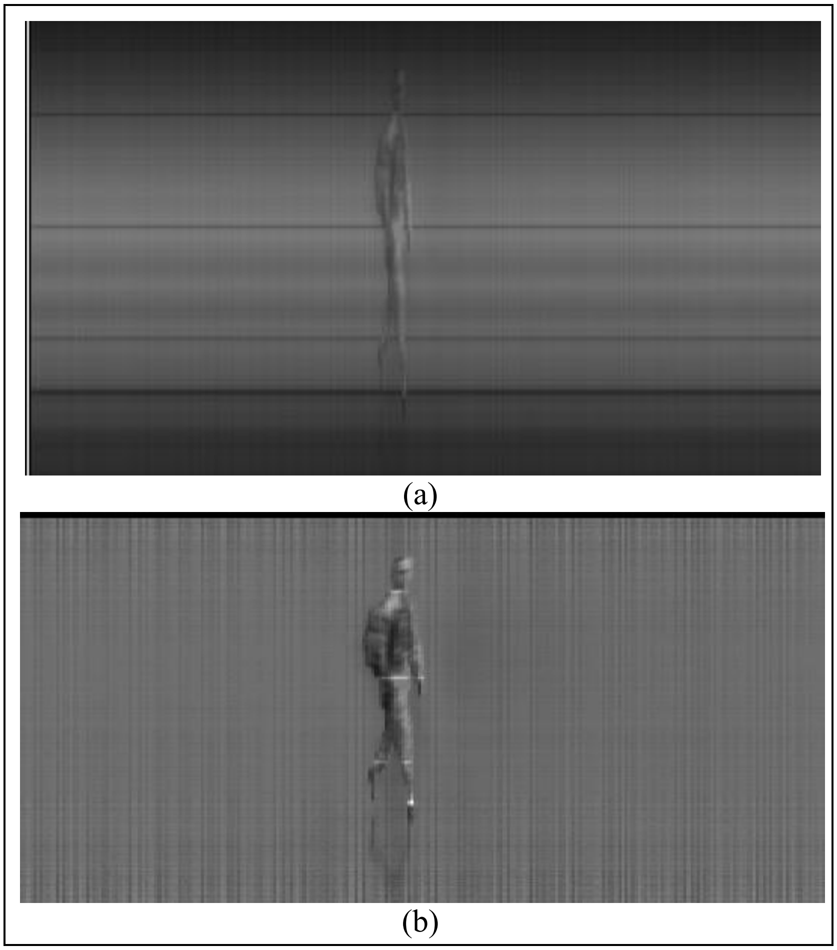
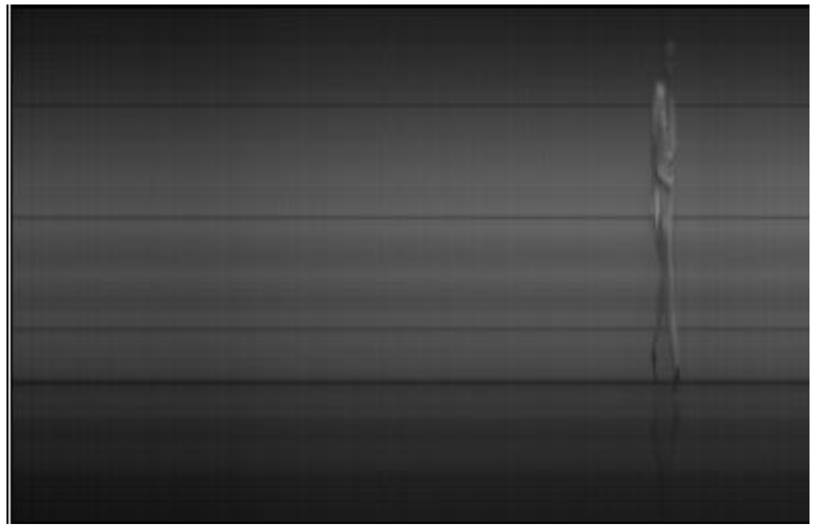
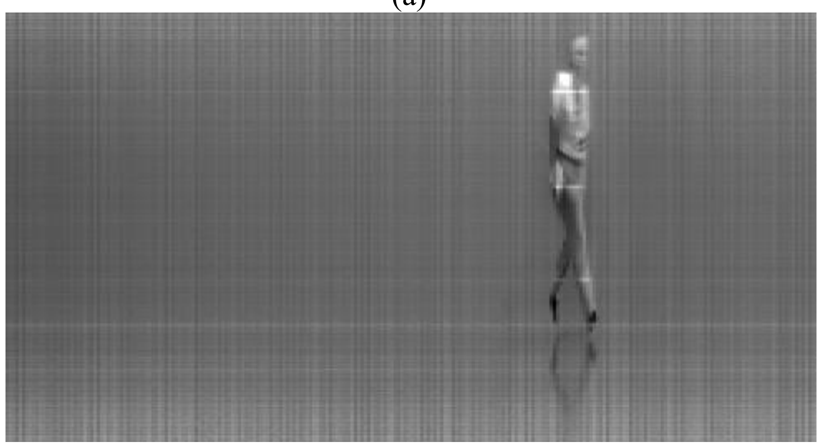


Figure 14. (a) Image of a person carrying a backpack, scanned at distance of about 18–20 ft and (b) processed image of figure 14a.



(a)



(b)

Figure 15. Image of a person moving with both hands folded in front, scanned at distance of about 18–20 ft and (b) processed image of figure 15a.

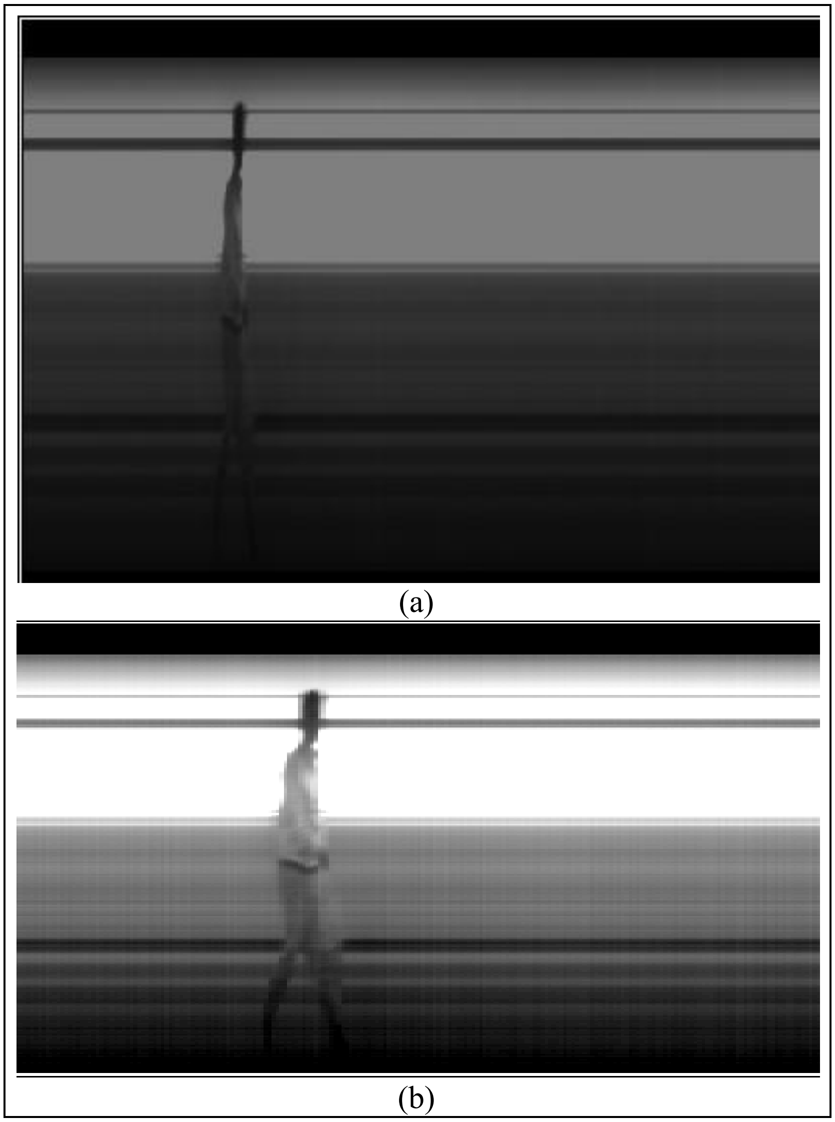


Figure 16. (a) Image of a person walking, scanned at distance of about 15 ft and (b) processed image of figure 16a.

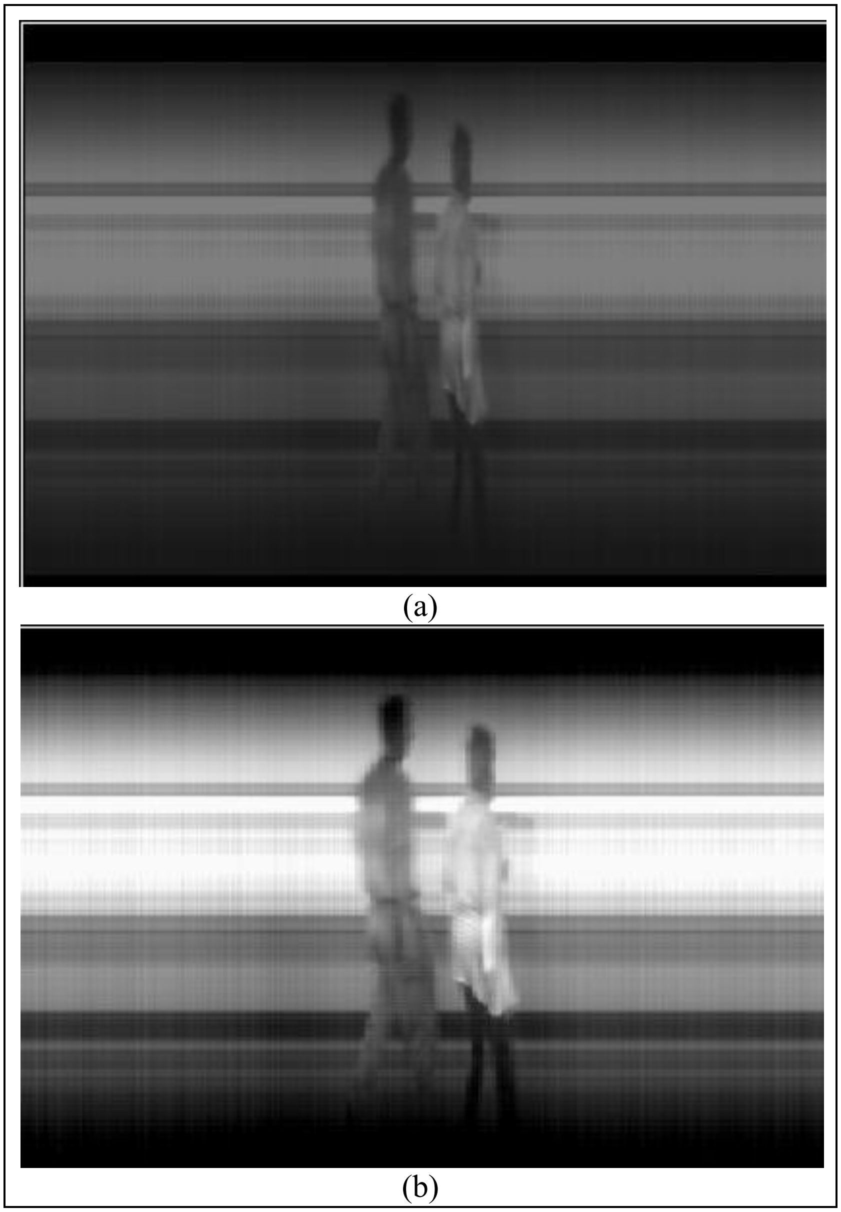


Figure 17. (a) Image of two people walking, scanned at distance of about 15 ft and (b) processed image of figure 17a.

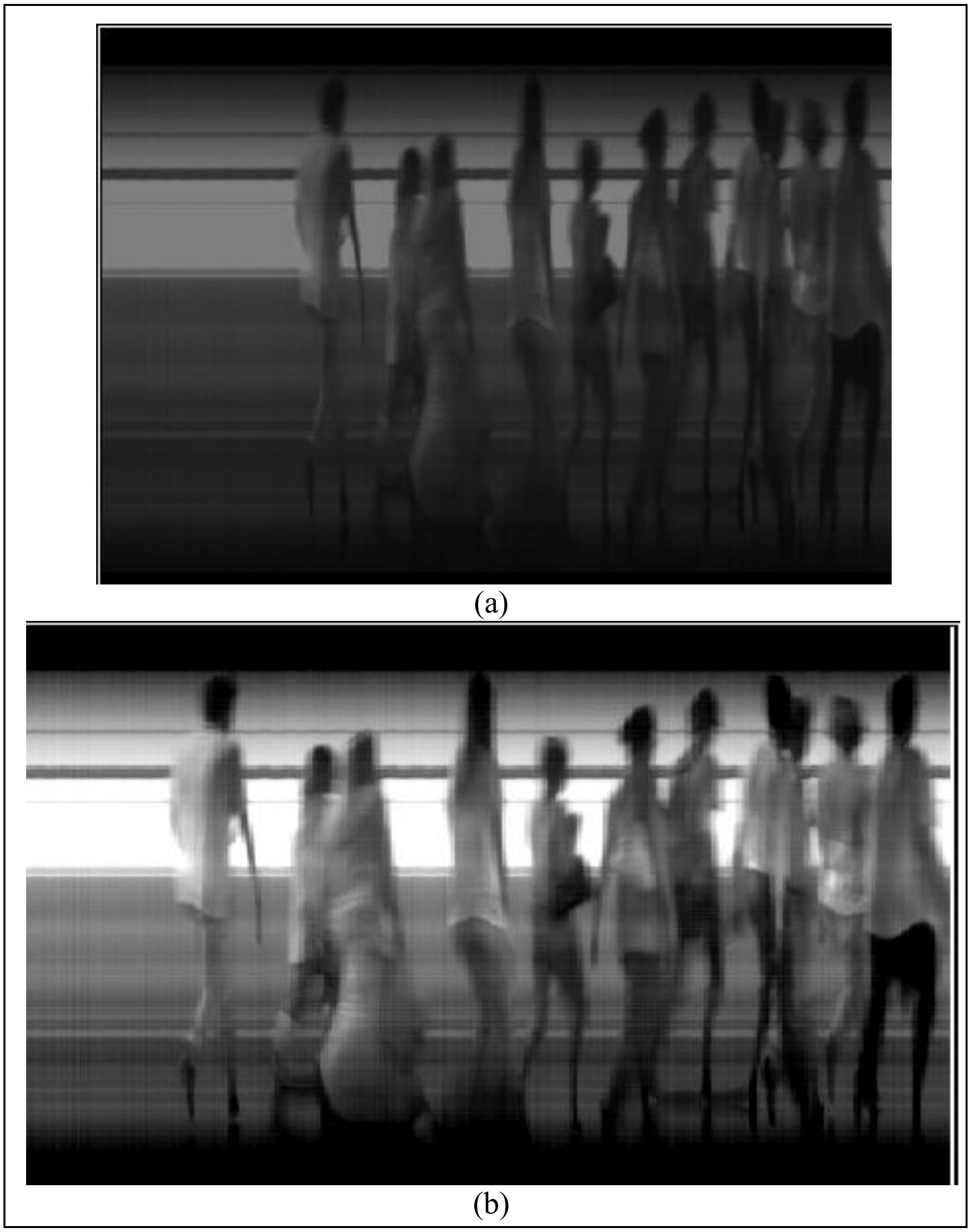
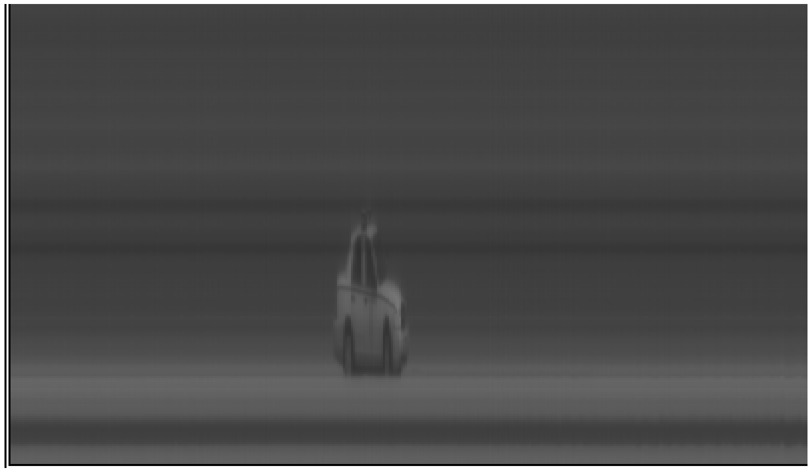
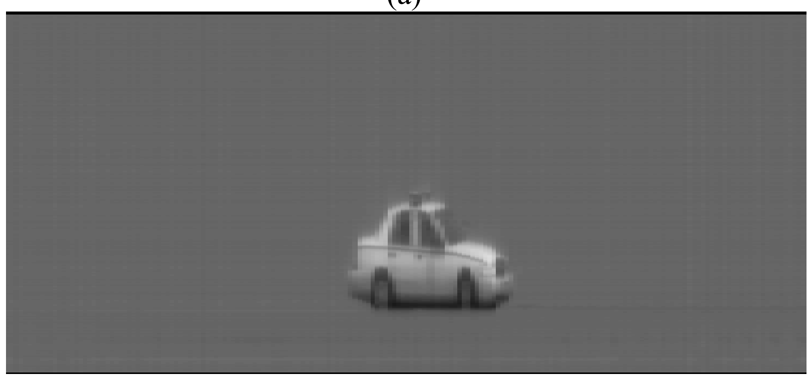


Figure 18. (a) Image of a group of people moving scanned at distance of about 12 ft and (b) processed image of figure 18a.

Figure 19. (a) Raw image of a moving SUV scanned at distance of about 50 m and (b) processed image of figure 19a.

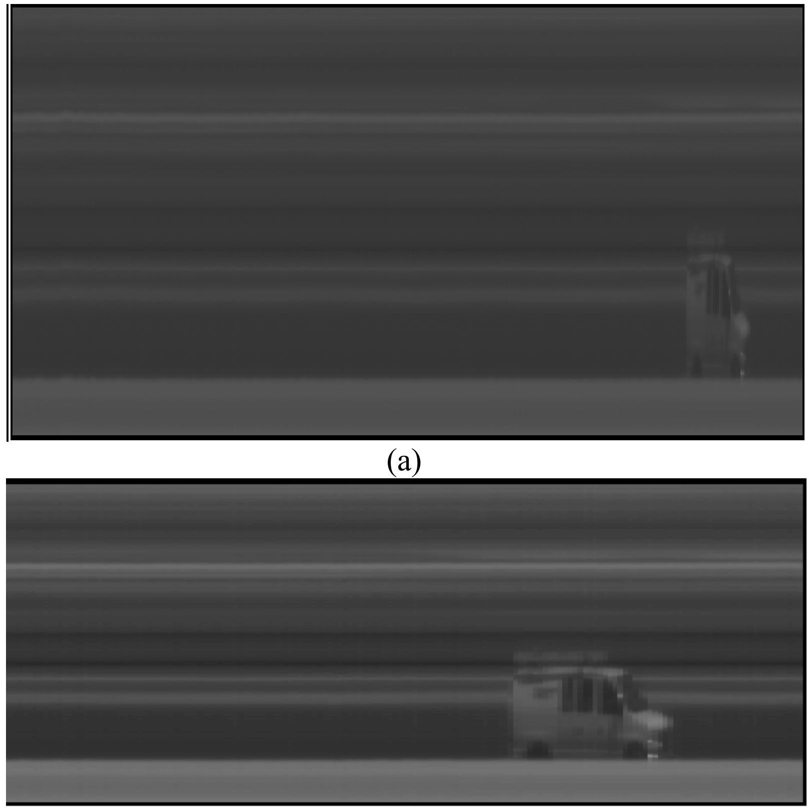


(a)



(b)

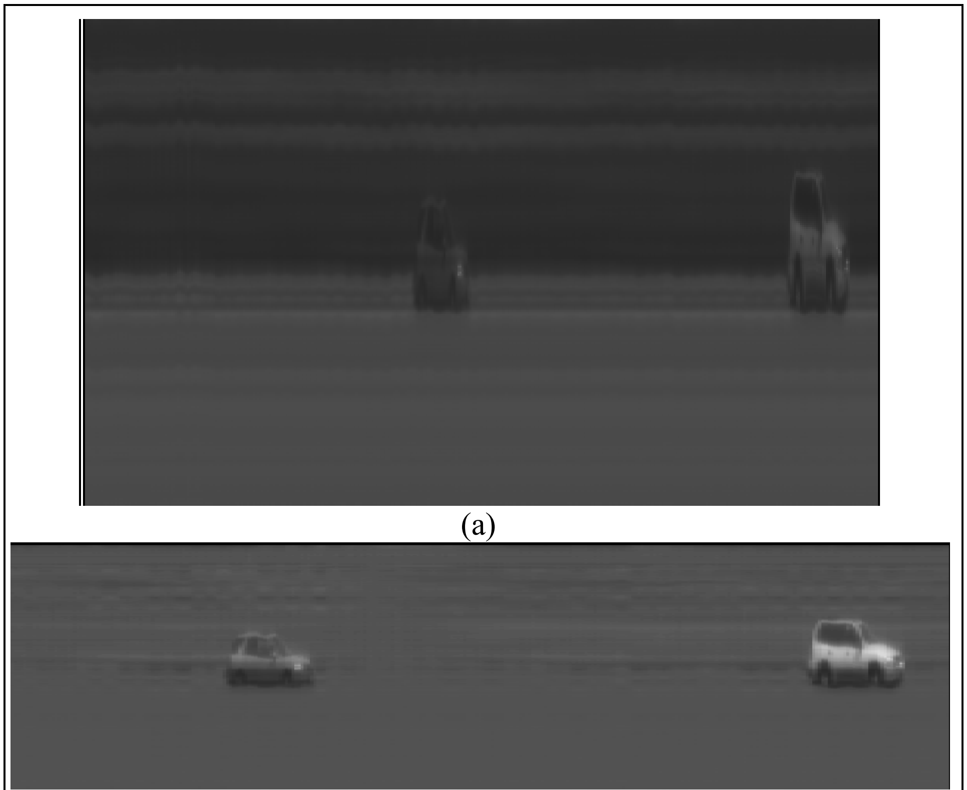
Figure 20. (a) Raw image of a moving vehicle scanned distance of about 50 m and (b) processed image of figure 20a.



(a)

(b)

Figure 21. (a) Raw image of a moving utility truck scanned distance of about 60 m and (b) processed image of figure 21a.



(a)

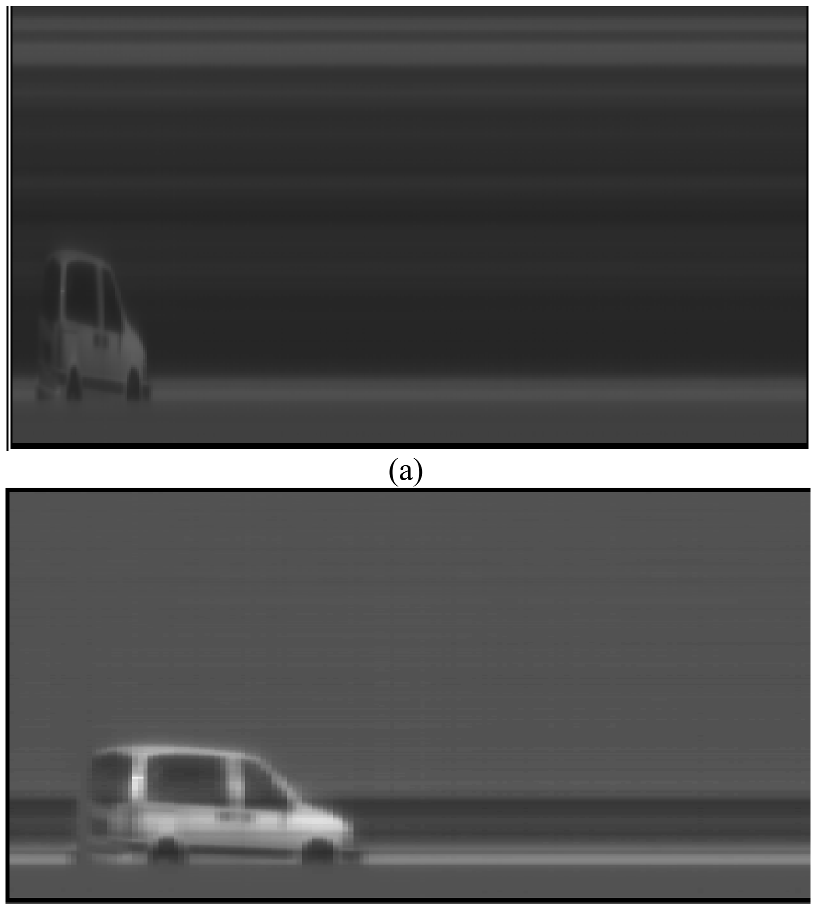
(b)

Figure 22. (a) Raw image of two vehicles and (b) processed image of figure 22a.

(a)

(b)

Figure 23. (a) Raw image of a moving van scanned distance of about 50 m and (b) processed image of figure 22a.

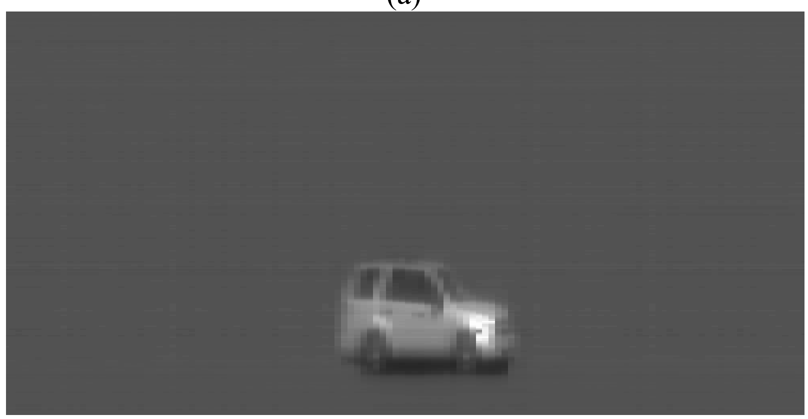


(a)

(b)

Figure 24. (a) Raw image of a moving van scanned distance of about 50 m and (b) processed image of figure 23a.

(a)



(b)

Figure 25. (a) Raw image of a moving van scanned distance of about 50 m and (b) processed image of figure 24a.

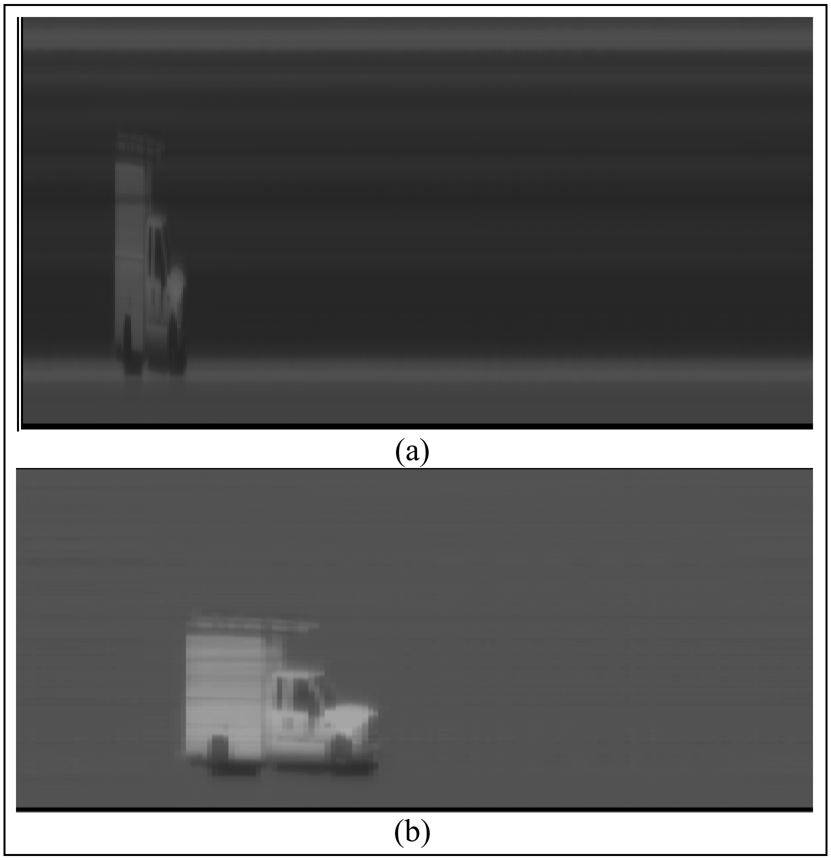
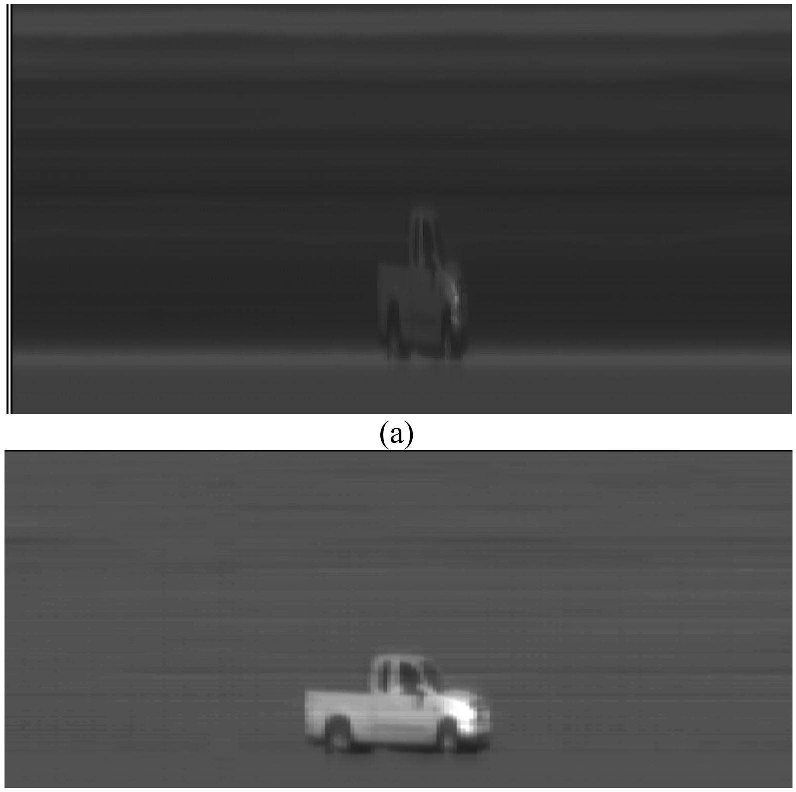


Figure 26. (a) Raw image of a moving utility truck scanned at distance of about 50 m and (b) processed image of figure 25a.



(a)

(b)

Figure 27. (a) Raw image of a moving truck scanned at distance of about 50 m and (b) processed image of figure 26a.

In each of the figures, —a is the scanned raw image as obtained from the system, and –b” is the corresponding processed image Processing includes *x*-axis scaling, and depending on the image, may include any of the following: brightness/contrast/gamma (BCG) adjustments, background subtraction, and filtering. The *x*-axis scaling is needed to correct for the –varying width” of the object in the raw image, due to its dependence on the moving speed. A slow-moving object results in a more –stretched” image and a fast-moving object results in a more –compressed” looking image in the time scale (the *x*-axis) of the profile raw image. The *x*-axis scaling minimizes this effect to produce profile image of object with more proper *x*-*y* aspect ratio. The BCG adjustments are needed because the lenses are all manual type, lacking automatic iris control; in fact, the BK7 lens has a fixed lens opening. BCG processing corrects or minimizes the effect caused by improper lens opening or exposure. Background subtraction can result in a profile image of an object with a flat or uniform background, as shown in figures 19–20. Depending on condition of the background, however, it is only effective when the background intensity variation stays fairly constant during the acquisition time for the 400 frames that make up the temporal profile image. It would not work very well, for example, when the sensor is looking at a background consisting of trees with their leaves and branches constantly moving back and forth by the blowing wind, or when the background consists of high contrast areas such as those shown in figures 22 and 17, respectively. Laplacian filters were used to process the raw

images in figures 13–15 to extract the contour of the object and outline the details, in addition to background subtraction.

The images in figures 13–18 were captured using a regular lens (specifically, a TV zoom lens, 12.5–75 mm f/1.8) that is designed for and used in the visible region, and thus is not optimized to operate at the SWIR range. The BK7 lens cannot be used here due to its limited FOV and fixed small aperture opening. These images were taken indoors with artificial light containing little SWIR wavelength. The sharp varying background brightness in the images of figures 16–18 is due to the fact that the sensor was pointing at a scene with a window at the upper portion (bright area) and a wall at the lower portion (dark area). Light coming from the window is mostly in the visible range, with most of SWIR energy filtered out by the window glass. The system, nevertheless, was able to capture temporal images of moving objects with sufficient detail and grey-shades.

The images in figures 19–26 were captured in the environment more in line at which the system design was intended to operate. The images were taken under sunlight (in mid afternoon) with moving objects approximately 50 m away, using lens that was designed for the distance with glasses made with a BK7 material that passes SWIR wavelengths. The resultant profile images showed much better image quality than those obtained indoors. Each vehicle's type, shape, and size can easily be identified and distinguished from each other.

6. Conclusion

We have developed a 1-D line scan imaging system using a 256 pixel InGaAs linear array sensor that operates at the SWIR (0.8–1.7 um) range, a PC controller, and a software algorithm in LabVIEW that can detect moving objects and provide temporal profiling images of the objects showing sufficient detail of their outline, shape, size, and height. It can also produce detailed grayscale levels using lens made of a BK7 material that passes SWIR wavelengths, as well as regular lens that operates at the visible region. The details provided in the scan images after processing are comparable to those in regular 2-D images in terms of allowing the viewer to easily identify the object as a person, group of people, or type of vehicles with high degree of accuracy.

The operating range of the system has been tested, ranging from short distances of 3–20 ft indoors to longer distances of up to 150 ft outdoors. At close distances of about 3–5 ft, it has a resolution sufficient enough to detect and capture profile image of 1-mm-thick moving object, as shown in figure 12. At distances of 10–20 ft, it is capable of acquiring profile images of people moving with light mostly in the visible region indoor, as shown in figures 13–18. At distances of up to 50 m, it can capture temporal images of moving vehicles with sufficient details and

grayscales that are comparable in many respects to those obtained with a 2-D focal plan array sensor, as shown (after some processing) in figures 19–27.

The performance and capabilities of the system, together with the inherent benefits associated with SWIR operation, are well suited for the various covert Intelligence, Surveillance and Reconnaissance (ISR) operations in military or border security environments. In addition, the system is relatively inexpensive. Its $5K (approximately) cost is estimated to be about 10–20% of what a regular 2-D SWIR imaging system costs.

With further study and investigation, the performance of the system can be enhanced. The following are some possible areas that may be worth exploring:

1. *Improve optical performance*: Optics plays an important role in forming the image to the sensor and is one of the limiting factors in the current design for obtaining good output images from the system. The following are some areas that merit further investigation:

   a. Increase the operating range by investigating system performance at longer distances with appropriate optics, i.e., up to 1 km.

   b. Investigate optic designs that provide wide depth-of-focus (DOF) and FOV ranges to make the system more versatile.

   c. Use lenses with zoom and auto iris control capabilities, together with suggestions a and b.

2. *Shorten setup time*: Unlike focal plane array sensor where an image of the target area can easily be obtained so location of the profiling sensor array can quickly and precisely be determined on the image, the linear array sensor cannot provide an image of the intended target area without first going through many iterations of scan and position adjustment process. The process is time consuming and requires delicate adjustments, especially when target distance is large. For the system to be practical, this setup process needs to be shortened. Methods to improve the setup process need to be investigated.

3. *Increase the refresh rate*: The current design operates at a refresh rate of about 53 Hz, which is sufficient for relatively slow-moving objects. For fast-moving objects, such as a vehicle moving at high speed at close distance, the refresh rate of the sensor needs to be increased to keep up with the fast changing rate of the image data that occurs at each frame update. This, in turn, requires higher processing power, faster data acquisition, etc. Various hardware (i.e., CPU, DAQ, etc.) speed and performance requirements need to be investigated to accommodate high refresh rate operations.

7. References

1. Chiu, David Y.T.; Alexander, Troy. *Development of a Profiling Scanner*; ARL TR-4573; U.S. Army Research Laboratory: Adelphi, MD, September, 2008

2. Article titled: 2D Laser Profiling Scanner for Detecting Targets. in *Engineering Solutions for Military & Aerospace Defense* June 2009, *3* (3).

INTENTIONALLY LEFT BLANK.

Appendix A. LabVIEW Program

Figure A-1 through A-4 details the screens of the LabVIEW program.

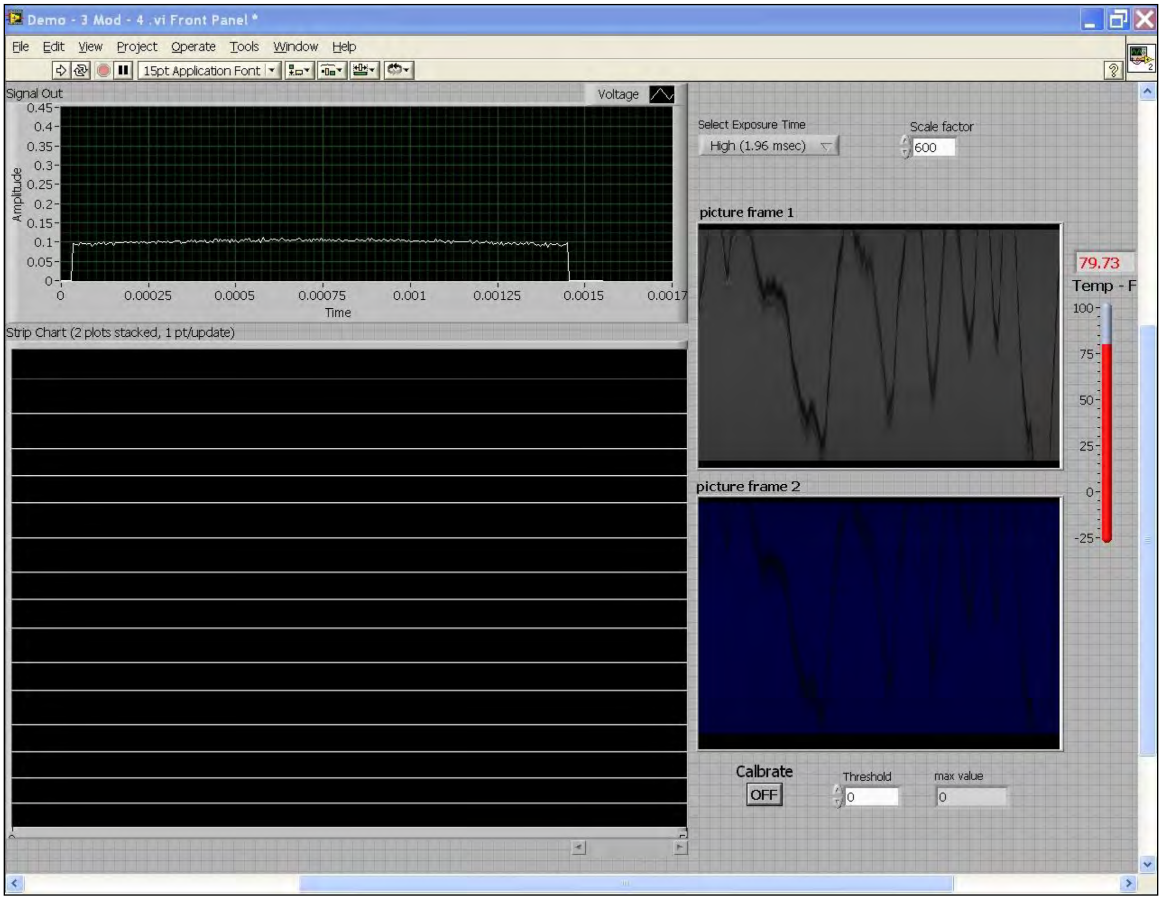


Figure A-1. Front panel.

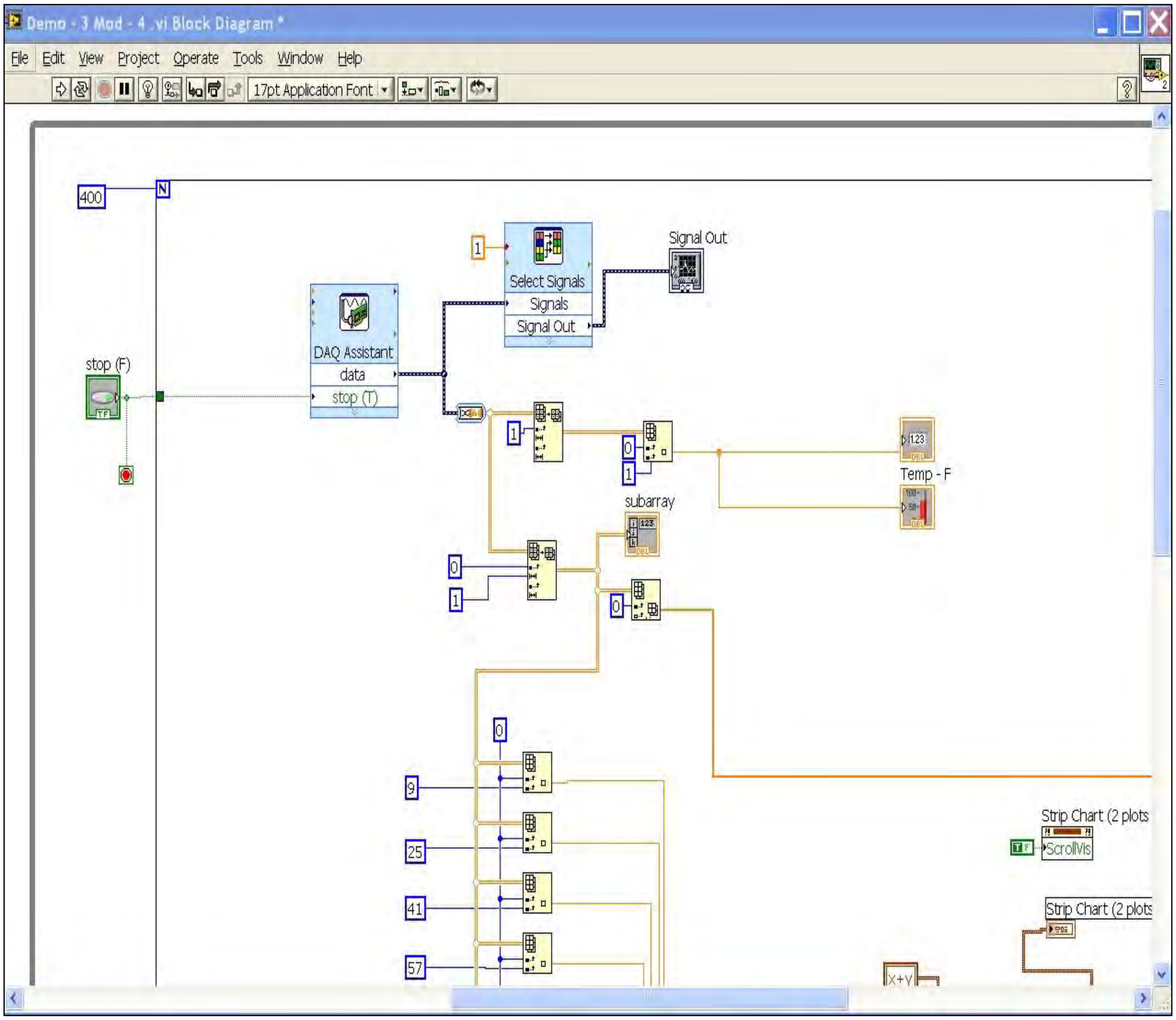


Figure A-2. Block diagram 1.

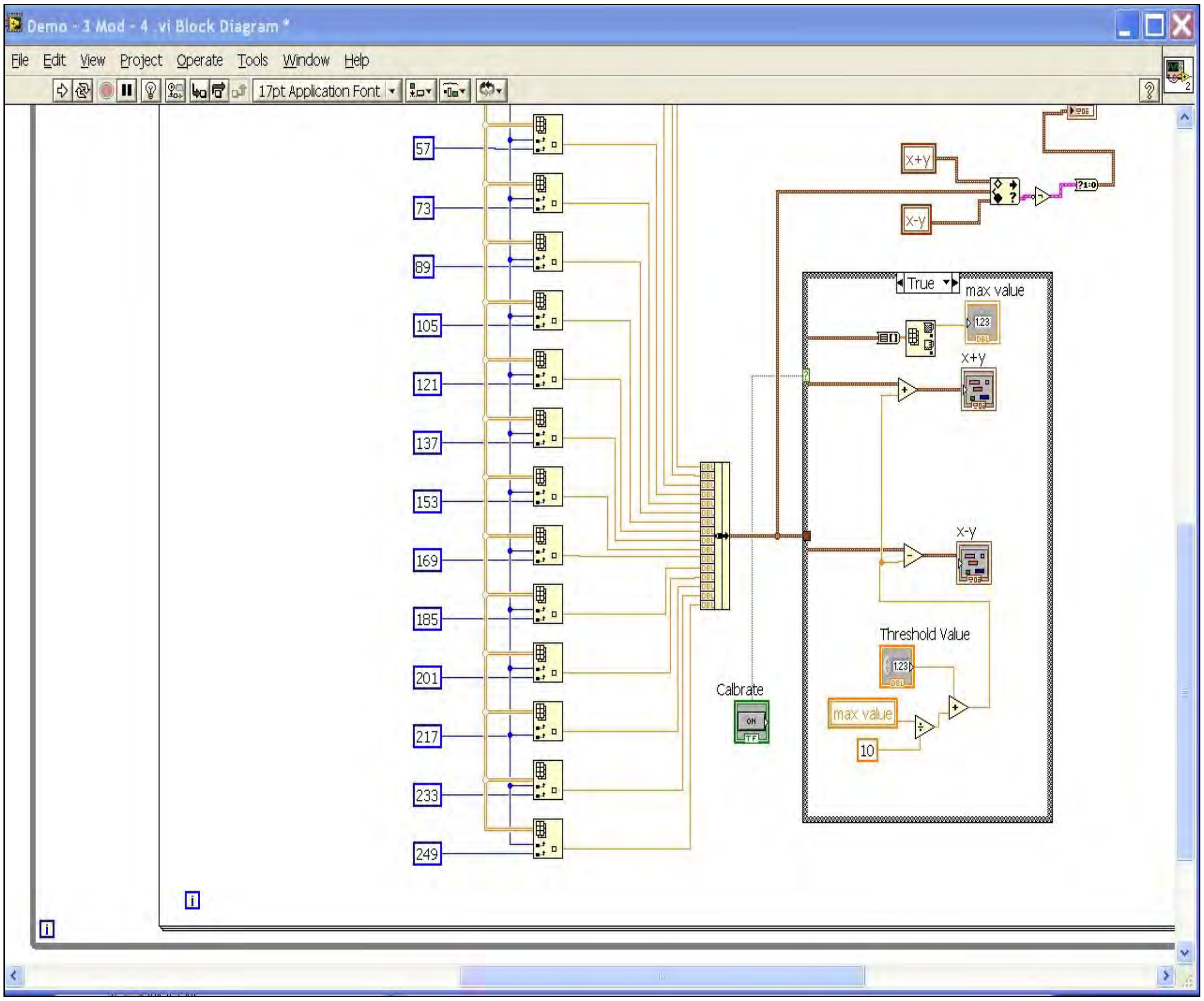


Figure A-3. Block diagram 2.

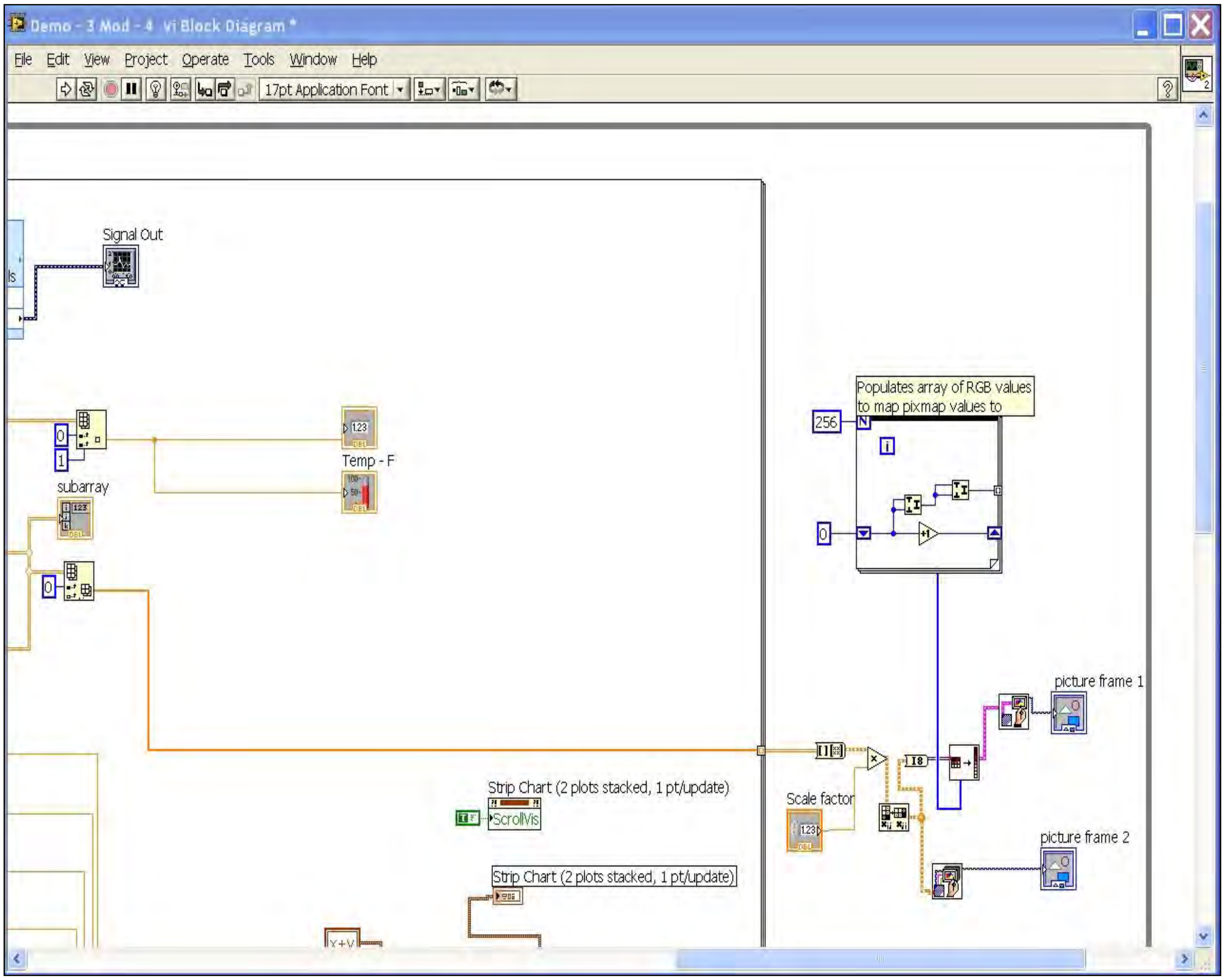


Figure A-4. Block diagram 3.

Appendix B. Calculation of Thermistor Resistances and Temperature Readings

From the data sheet, the nominal resistance of the thermistor is 5000 ohms at 25 °C and the temperature calculation for the thermistor resistance is given by the equation

$$1 / T = A + B \ln (R2) + C(\ln(R2))^3, \quad \text{(B-1)}$$

where *T* is in units of Kelvin (0 °C = 273.15 K) and *R2* is in units of ohms, using the constants,

A = 1.2891x10-3

B = 2.3561x10-4

C = 9.4272x10-8

with an accuracy of ±0.5 °C in the range of 0 to 40 °C.

Table B-1 shows the calculation for temperature reading (T), and resistor R2,

$$D = \mathrm{Ln}\ (R2),$$

$$E = (\mathrm{Ln}\ (R2))^3$$

$$F = B * \mathrm{Ln}\ (R2),$$

$$G = C * (\mathrm{Ln}\ (R2))^3.$$

Table B-1. Calculation for temperature reading (T), and resistor R2.

			$R_T = R_1 + R_2$			D	E	F	G		1 / (A+F+G)	K -273
Temp (°F)	**Temp (°C)**	**R2 = Resistance**	**401000 + R_2**	**5 * R2**	**V2**	**Ln (R2)**	**(Ln (R2))^3**	**B * Ln (R2)**	**C * (Ln R2)^3**	**A + F + G**	**Temp (K)**	**Temp (°C)**
–31	–35	121968	522968	609840	1.1661	11.71	1.61E+03	2.76E-03	1.51E-04	4.20E-03	238.11	–34.89
–22	–30	88937	489937	444685	0.9076	11.40	1.48E+03	2.68E-03	1.40E-04	4.11E-03	243.11	–29.89
–13	–25	65536	466536	327680	0.7024	11.09	1.36E+03	2.61E-03	1.29E-04	4.03E-03	248.10	–24.90
–4	–20	48633	449633	243165	0.5408	10.79	1.26E+03	2.54E-03	1.18E-04	3.95E-03	253.15	–19.85
5	–15	36539	437539	182695	0.4176	10.51	1.16E+03	2.48E-03	1.09E-04	3.87E-03	258.15	–14.85
14	–10	27704	428704	138520	0.3231	10.23	1.07E+03	2.41E-03	1.01E-04	3.80E-03	263.16	–9.84
23	–5	21190	422190	105950	0.251	9.96	9.88E+02	2.35E-03	9.32E-05	3.73E-03	268.16	–4.84
32	0	16344	417344	81720	0.1958	9.70	9.13E+02	2.29E-03	8.61E-05	3.66E-03	273.16	0.16
41	5	12707	413707	63535	0.1536	9.45	8.44E+02	2.23E-03	7.96E-05	3.60E-03	278.16	5.16
50	10	9956	410956	49780	0.1211	9.21	7.80E+02	2.17E-03	7.36E-05	3.53E-03	283.16	10.16
59	15	7859	408859	39295	0.0961	8.97	7.22E+02	2.11E-03	6.80E-05	3.47E-03	288.16	15.16
68	20	6247	407247	31235	0.0767	8.74	6.68E+02	2.06E-03	6.29E-05	3.41E-03	293.16	20.16
77	25	5000	406000	25000	0.0616	8.52	6.18E+02	2.01E-03	5.82E-05	3.35E-03	298.15	25.15
86	30	4027	405027	20135	0.0497	8.30	5.72E+02	1.96E-03	5.39E-05	3.30E-03	303.15	30.15
95	35	3264	404264	16320	0.0404	8.09	5.30E+02	1.91E-03	4.99E-05	3.25E-03	308.15	35.15
104	40	2662	403662	13310	0.033	7.89	4.91E+02	1.86E-03	4.62E-05	3.19E-03	313.14	40.14
113	45	2183	403183	10915	0.0271	7.69	4.54E+02	1.81E-03	4.28E-05	3.14E-03	318.13	45.13
122	50	1800	402800	9000	0.0223	7.50	4.21E+02	1.77E-03	3.97E-05	3.09E-03	323.13	50.13

List of Symbols, Abbreviations, and Acronyms

1-D	one-dimensional (1-D)
2-D	two-dimensional
3-D	three-dimensional
ARL	U.S. Army Research Laboratory
BCG	brightness/contrast/gamma
DAQ	data acquisition module
DOF	depth of focus
FOV	field of view
InGaAs	indium gallium arsenide
IR	infrared
SWIR	short wave IR
TA	threshold adjusted

No. of Copies	Organization
1 ELEC	ADMNSTR DEFNS TECHL INFO CTR ATTN DTIC OCP 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
3 HCS	US ARMY RSRCH LAB ATTN IMNE ALC HRR MAIL & RECORDS MGMT ATTN RDRL CIO LL TECHL LIB ATTN RDRL CIO MT TECHL PUB ADELPHI MD 20783-1197
13 HCS	US ARMY RSRCH LAB ATTN RDRL SEE-E DAVID CHIU (10 HCs) TROY ALEXANDER KEITH ALIBERTI PAUL PELLEGRINO 2800 POWDER MILL ROAD ADELPHI MD 20783-1197
1	DARPA MTO ATTN N. DHAR 3701 NORTH FAIRFAX DR ARLINGTON VA 22203-1714
1 CD	OFC OF THE SECY OF DEFNS ATTN ODDRE (R&AT) THE PENTAGON WASHINGTON DC 20301-3080
1	US ARMY RDECOM CERDEC NIGHT VISION & ELECTRONIC SENSORS DIRECTORATE ATTN RDER-NVG-RG (JOE W. PAPA) 10221 BURBECK ROAD FORT BELVOIR VA 22060-5806

No. of Copies	Organization
1	COMMANDER US ARMY RDECOM ATTN AMSRD AMR W.C. MCCORKLE 5400 FOWLER RD REDSTONE ARSENAL AL 35898-5000
1	US GOVERNMENT PRINT OFF DEPOSITORY RECEVING SECTION ATTN MAIL STOP IDAD J. TATE 732 NORTH CAPITAL ST N.W. WASHINGTON DC 20402
1	HQ USSOCOM ATTN SORDAC-RA (TILO) 7701 TAMPA POINT BLVD MACDILL AFB FL 33621-5323
1	DIRECTOR US ARMY RSRCH LAB ATTN RDRL ROE L W CLARK PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709
1	US ARMY RSRCH LAB ATTN RDRL SEE G. WOOD 2800 POWDER MILL ROAD ADELPHI MD 20783-1197

TOTAL 25 (1 ELEC, 23 HCS, 1 CD)